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1 **Tropical rainfall over the last two millennia: evidence for a low-latitude**
2 **hydrologic seesaw**

3

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25

26 **Abstract**

27 **The presence of a low- to mid-latitude interhemispheric hydrologic seesaw is**
28 **apparent over orbital and glacial-interglacial timescales, but its existence over**
29 **the most recent past remains unclear. Here we investigate, based on climate**
30 **proxy reconstructions from both hemispheres, the inter-hemispherical phasing**
31 **of the Intertropical Convergence Zone (ITCZ) and the low- to mid-latitude**
32 **teleconnections in the Northern Hemisphere over the past 2000 years. A clear**
33 **feature is a persistent southward shift of the ITCZ during the Little Ice Age until**
34 **the beginning of the 19th Century. Strong covariation between our new**
35 **composite ITCZ-stack and North Atlantic Oscillation (NAO) records reveals a**
36 **tight coupling between these two synoptic weather and climate phenomena over**
37 **decadal-to-centennial timescales. This relationship becomes most apparent when**
38 **comparing two precisely dated, high-resolution paleorainfall records from Belize**
39 **and Scotland, indicating that the low- to mid-latitude teleconnection was also**
40 **active over annual-decadal timescales. It is likely a combination of external**
41 **forcing, i.e., solar and volcanic, and internal feedbacks, that drives the**
42 **synchronous ITCZ and NAO shifts via energy flux perturbations in the tropics.**

43

44 Hemispheric antiphasing of large-scale precipitation patterns in low- and mid-latitude
45 regions, driven by the seasonal migration of the Intertropical Convergence Zone
46 (ITCZ), has been described over orbital timescales, Dansgaard-Oeschger (DO), and
47 Heinrich events¹⁻³. As part of the upward limb of the Hadley Cells, the ITCZ plays a
48 crucial role in global energy redistribution. Temperature-driven meridional
49 displacement of the tropical Hadley Cells and the ITCZ^{4,5} induced synchronous shifts
50 in higher latitude climate patterns¹ on millennial timescales. High signal-to-noise

51 ratios of millennial-scale climate shifts during glacial periods, largely due to different
52 boundary conditions related to the presence of extensive continental ice sheets,
53 facilitate their detection in proxy records.

54 Although this atmospheric reorganization has been described over glacial-interglacial
55 timescales, the dynamics and latitudinal extent of this interhemispheric hydrologic
56 seesaw¹ over the most recent past are still poorly understood. Additionally,
57 chronological uncertainties, although less significant than in Pleistocene
58 reconstructions, and low signal-to-noise ratios in Holocene paleoclimate records can
59 hinder interpretations of rapid climate change, and this is particularly true over the last
60 few millennia.

61

62 Here we investigate the latitudinal extent of the hydrologic seesaw in the Northern
63 Hemisphere (NH) over the past two millennia by comparing precisely dated, high-
64 resolution paleo-rainfall records from low- and mid-latitudes. We reconstruct broad
65 ITCZ migrations using 25 published high-resolution stalagmite, sediment, tree ring,
66 and ice core records from both hemispheres identified as reflecting low-latitude,
67 ITCZ-driven rainfall, before extending the comparison to NH mid-latitudes. Details of
68 the incorporated records are presented in Suppl. Table 1. Because our reconstruction
69 focuses on the total extent of hemispheric displacement of the ITCZ, only records
70 experiencing one annual passage of the ITCZ or with a clear bias towards one rainy
71 season are considered. Records were selected based on sampling resolution (< 15
72 years on average), chronological precision (mean 2σ error < 40 years), and location,
73 in order to maximize spatial coverage and interpretative value (Fig. 1). To reconstruct
74 long-term ITCZ migration dynamics, the records were combined into hemispheric
75 stacks relative to their location (Fig. 2), and then to an overall ITCZ-stack (Fig. 3), by

76 bringing them onto a common timescale and averaging their signal (normalized as z-
77 scores, see Methods). To confirm that no bias was introduced with our selection of
78 records, a second stack was compiled, which included records that did not strictly
79 meet the selection criteria (due to low resolution and/or insufficiently precise dating).
80 Comparison between the two stacks shows very little difference, indicating that our
81 selection of records captures trends at the global scale (Suppl. fig. 1).

82

83 Stacking the records for each hemisphere results in positive z-scores indicating drier
84 conditions, and negative z-scores indicating wetter conditions (Fig. 2). Due to
85 chronological uncertainties, we consider only decadal-centennial scale trends within
86 these stacks. Both hemispheric stacks show relatively stable conditions between 0 to
87 ~1320 C.E., with the exception of a dry interval evident in some NH records during
88 the 11th Century (Fig. 2A). This 11th Century excursion is not observed in SH records
89 (Fig. 2B). The most prominent, and hemispherically antiphased, shift in both records
90 occurred between 1320-1820 C.E., indicating a pronounced southward displacement
91 of the ITCZ during this period (Fig. 2C). These longer-term features become even
92 more apparent when the two stacks are combined into one ITCZ-stack record,
93 reflecting the deflection of the ITCZ over the past 2000 years (positive – ITCZ is
94 positioned more northwards, negative – ITCZ is positioned more southwards). In this
95 combined record the most pronounced period of southward deflection of the ITCZ
96 also occurred between 1320 and 1820 C.E. (Fig. 3).

97

98 We then investigated the long-term (decadal-centennial scale) latitudinal extent of this
99 hydrologic seesaw between tropical regions and the mid-latitude North Atlantic by
100 comparing the ITCZ-stack to a recent 1000-year-long, model-constrained North

101 Atlantic Oscillation (NAO_{mc}) reconstruction based on records spanning broad regions
102 of the western NH⁶ (Fig. 3). NAO_{mc} also includes datasets from high latitudes (i.e.,
103 northern Canada, Greenland, northern Scandinavia), but because the NAO is a leading
104 pattern of weather and climate variability in the NH mid-latitudes⁷ it is indicative of
105 mid-latitude hydroclimate conditions. Comparison of decadal-centennial trends in
106 both reconstructions reveals compelling similarities ($r = 0.78$, $p < 0.001$, calculated
107 using standard correlation and a prior transformation of the time series to normal
108 distribution, Fig. 3), implying that ITCZ migration and NAO variability were closely
109 coupled over the last 1,000, and most likely the last 2,000, years.

110

111 Two very precisely dated, high-resolution records constrain higher frequency
112 hydroclimate variability from the low- and mid-latitudes, since small-scale variability
113 is averaged out in the ITCZ stacks (Fig. 4, Suppl. Fig. 2). We use stable carbon
114 isotope ratios ($\delta^{13}\text{C}$) from stalagmite YOK-I from Yok Balum Cave in southern
115 Belize⁸ as the low-latitude end-member, because it is one the highest resolved (0.5
116 years on average) and best dated (mean error 3.3 years) records from the ITCZ-stack
117 that covers the entire period of the reconstruction (Suppl. Table 1). Variations in $\delta^{13}\text{C}$
118 at this cave site have previously been attributed to variations in rainfall registered
119 above the cave, governed by the seasonal migration of the ITCZ^{8,9}. Therefore, $\delta^{13}\text{C}$ at
120 Yok Balum Cave is a more sensitive proxy to variations in regional rainfall amount
121 (and particularly drying) than $\delta^{18}\text{O}$, which is a mixed signal including precipitation
122 amount, moisture source, and storm path length^{9,10}. Yok Balum Cave is located at the
123 northernmost extent of the boreal summer ITCZ, a remarkably sensitive location to
124 record even small shifts in ITCZ position⁹. We compare the Belizean ITCZ record to
125 the well-dated growth-band width record from stalagmite SU-96-7 from Uamh-an-

126 Tartair Cave in Scotland¹¹. The SU-96-7 record is highly correlated to precipitation in
127 Scotland, and consequently to the winter NAO^{11,12}, and was also included in the
128 NAO_{mc} composite. This record was preferred over a more recent composite NAO
129 reconstruction from Scotland¹² (which includes SU-96-7), because of its higher
130 sensitivity to the NAO ($r = -0.70^{11}$ vs. $r = -0.46^{12}$), which may reflect different
131 hydrological pathways feeding the individual stalagmites in the composite records,
132 thus smoothing the NAO signal. This would likely remove high frequency trends,
133 leading to the loss of key events at the (sub)decadal scale.

134 The long-term trend in both records was identified and removed by using a Savitzky-
135 Golay smoothing filter, thus highlighting subdecadal-scale variations and facilitating
136 comparison (Suppl. Fig. 2). Several shared multi-annual drying events are clearly
137 present within both residual time series ($r = 0.51$, $p < 0.001$) (Fig 4, Suppl. Fig. 3).
138 Particularly notable is the almost century-long event recorded at both locations
139 between ~1020-1100 C.E., one of a series of multi-decadal droughts that contributed
140 to the transformation of Classic Maya society in Central America⁸. The similarity in
141 both the smoothed long-term trends and sub-decadal variations between the low-
142 latitude YOK-I record and the mid-latitude SU-96-7 record suggests that
143 teleconnections exist between these two locations, linked through the Bermuda-
144 Azores High.

145

146 Paleoclimate records covering the last glacial period have advanced the concept of the
147 interhemispheric hydrologic seesaw on millennial timescales; for example, marine
148 records from the Cariaco Basin and the Arabian Sea show pronounced long-term
149 southward displacement of the ITCZ during Heinrich stadials³. At the same time,
150 stalagmites from China record reduced summer precipitation and a weaker Asian

151 Summer Monsoon (ASM)^{13,14}. During Greenland warming episodes, stalagmite
152 records from Peru and Brazil show that this coincided with periods of decreased
153 South American Summer Monsoon (SASM) strength^{2,15}. Our stacked ITCZ record
154 reveals that hemispheric antiphasing of low latitude precipitation over the last 2000
155 years is due to meridional displacement of the ITCZ and related low-latitude climate
156 patterns, rather than of overall weakened precipitation in the tropics^{4,16}. The
157 hydrologic seesaw results from perturbations in tropical energy flux, e.g., due to
158 hemispheric temperature contrasts, as the ITCZ tracks the thermal equator^{17,18}.
159 Meridional displacement of the ITCZ triggers shifting of the Hadley cells in both
160 hemispheres¹⁷, and consequently drives circulation processes at higher latitudes. A
161 long-term global cooling trend^{19,20} coincident with a pronounced southward shift of
162 the ITCZ from ~1300 C.E. onwards support this hypothesis (Fig. 3). Globally cooler
163 temperatures would provoke a weakening of the Atlantic meridional overturning
164 circulation (AMOC) and increased Arctic sea ice, resulting in a southward shift of the
165 energy flux equator and the ITCZ¹⁷.

166

167 The Yok Balum, Forestry, and Dante Cave records are directly influenced by the
168 mean position of the ITCZ^{8,21–23} (with the Forestry Cave record being influenced
169 primarily by the South Pacific Convergence Zone, the most persistent spur of the
170 ITCZ^{23,24}). Monsoonal systems, like the ASM, the SASM, the Australian-Indonesian
171 Summer Monsoon (AISM), the Indian Summer Monsoon (ISM), and the West
172 African Monsoon (WAM) are affected by the hemispheric migration of the ITCZ as a
173 major moisture flux conduit and by hemispheric temperature, because land-sea
174 temperature contrasts drive the monsoonal systems^{17,25}. Although monsoonal
175 variations might not necessarily be equivalent to ITCZ shifts, monsoons can be linked

176 to ITCZ variations^{17,26–28}. The SASM (Huagapo, Cascayunga, Curupira, and Pau
177 d’Alho Caves, and Quelccaya Ice cap) and the AISM (Chillagoe Cave, KNI-51 Cave)
178 records used here are all antiphased with respect to the NH records on decadal-
179 centennial scales, indicating stronger SH monsoons when NH low latitudes are drier.
180 The similarities between these globally distributed records, and the consistent
181 hemispheric antiphasing over decadal-centennial timescales, are compelling and
182 suggest that the interhemispheric hydrologic seesaw was active, albeit in subdued
183 fashion compared to the Last Glacial, over the most recent past. However, more
184 precisely dated high-resolution records from the tropics are necessary to gain more
185 detailed insights into possible different regional expressions of hydroclimate
186 variability.

187
188 Propagation of meridional ITCZ shifts to mid-latitude regions in both hemispheres
189 occurred across millennial-scale climate shifts: for example, a stalagmite $\delta^{18}\text{O}$ record
190 from New Mexico, U.S., shows increased winter precipitation during NH cooling
191 phases⁵, and stalagmite growth frequencies in Korea and south-eastern Australia are
192 inversely correlated¹. Southward shifts of the ITCZ and the Hadley Cells during cold
193 phases reduce the meridional pressure gradient in the NH, inducing expansion and
194 southward displacement of the polar and mid-latitude pressure cells. Consequently,
195 the polar jet and westerlies shifted southward and weakened⁵, and monsoonal systems
196 propagated less far northward¹. At the same time, southward displacement and
197 compression of the SH pressure cells results in strengthening and southward displaced
198 mid- and high-latitude wind and weather patterns^{1,4,29}. The significant correlation
199 between our ITCZ-stack and the NAO_{mc} record indicates that these mechanisms very
200 likely existed during the last millennium, as well as during the Last Glacial. Colder

201 NH temperatures and a southward-shifted ITCZ would promote negative NAO
202 conditions, due to a lower meridional pressure gradient, as well as weakening and
203 southward shift of the NH westerlies, whereas a northward displacement of the ITCZ
204 may trigger a positive NAO³⁰ (Fig. 3). However, we cannot at present rule out the
205 potential influence of additional atmospheric mechanisms, e.g., related to changes in
206 moisture transport and convection activity along the ITCZ, as well as in the Walker
207 circulation and the El-Niño Southern Oscillation (ENSO), which could impact the
208 distribution of low-latitude rainfall patterns. Similarly, conditions in the North
209 Atlantic related to sea ice extent, temperature, and snow cover, could lead to
210 simultaneous, but unrelated changes in both the NAO and the ITCZ, possibly with
211 influences from the AMOC. In particular, the expression of these mechanisms will
212 greatly vary on the regional scale, and it is also possible that both realms react to a
213 certain extent independently to the common forcing from hemispheric or global
214 temperature gradients.

215

216 The two millennia preceding industrialization were characterized by a long-term
217 cooling trend, culminating in a well-documented period of globally colder conditions,
218 the Little Ice Age (LIA, ~1200-1850 C.E.)^{19,20,31}. The presence of a globally
219 synchronous warm period between ~950-1200 C.E.³², the Medieval Climate Anomaly
220 (MCA), is being challenged by more recent global temperature reconstructions^{19,20},
221 and is also not expressed as a change in the latitudinal position of the ITCZ in our
222 stacked ITCZ records (Fig. 3). However, it is noteworthy that three out of the six NH
223 records included in the stack that cover the MCA interval indicate drier conditions
224 between 1000-1100 C.E. (Fig. 2), and both high-resolution records considered here,
225 YOK-I and SU-96-7, show simultaneous and persistent drying occurring in Scotland

226 and Belize between 1020-1100 C.E. (Fig. 4). These records support tree ring
227 reconstructions from Europe and North America^{33,34}, and lake sediment
228 reconstructions from equatorial Africa³⁵, all reflecting regional NH drought during the
229 11th century C.E. At the same time, wetter conditions were registered in a stalagmite
230 record from Madagascar (15°S)³⁶. It is possible that this resulted from reduced solar
231 irradiance during the contemporaneous Oort solar minimum (centered around 1050
232 C.E.).

233 The low-latitude hydroclimate records discussed here all suggest a southward ITCZ
234 shift broadly synchronous with the LIA (here 1320-1820 C.E.), and that the ITCZ
235 only began migrating northwards again after ~1820 C.E., with the beginning of the
236 Current Warm Period (CWP) (Fig. 3). The persistence of LIA cooling has been
237 documented before and appears to be globally expressed¹⁹, consistent with the
238 concept of an energy flux perturbation in the tropics and associated southward
239 displacement of the ITCZ due to weakening of the AMOC (and increased ice cover in
240 the Arctic Ocean)¹⁷ (Fig. 3). The causes for the extensive LIA cooling in the NH
241 remain enigmatic, but volcanic forcing appears to have been dominant during this
242 time^{19,31,37}. Stratospheric sulfate aerosols from explosive volcanic eruptions affect
243 climate on annual to decadal timescales via scattering and absorption of solar
244 radiation³⁸⁻⁴⁰. Large NH volcanic eruptions have been linked to hemispheric
245 displacement of the ITCZ and related circulation patterns by cooling the hemisphere
246 of the eruption, resulting in hemispheric temperature asymmetries^{9,16,18,29}. Several
247 large volcanic eruptions occurred during the late 13th century most notably the 1257
248 C.E. Samalas/Rinjani eruption⁴¹, with an estimated sulfate load of 73 kg km⁻² 42.
249 Protracted global cooling may have resulted from the amplifying effects of expanding
250 sea ice and snow cover in northern latitudes^{31,43}.

251 Changes in solar activity are another proposed cause for the widespread NH cooling
252 during the LIA⁴⁴⁻⁴⁷. A cluster of four significant “grand solar minima” occurred
253 within the LIA, whereas solar activity during previous centuries was higher. It is
254 possible that the combination of low solar activity and NH volcanic eruptions with
255 associated feedbacks (such as from increased sea ice and more frequent atmospheric
256 blocking events over the North Atlantic)^{31,47} between 1250-1800 C.E.^{31,47}, led to the
257 LIA cooling and southward ITCZ displacement. The importance of insolation changes
258 is however much smaller than that of volcanic eruptions in terms of radiative forcing.
259 It is therefore likely that the volcanic forcing dominated, while changes in solar
260 activity enhanced these trends.

261

262 It is worth noting that some of the short-lived events in the Scottish and Belizean
263 high-resolution records appear linked with the volcanic record: the clearest connection
264 appears between the 1783 C.E. *Laki/Grimsvötn* eruption, the largest NH eruption of
265 the last 1000 years in terms of sulfate loads⁴⁰, occurring synchronously with strong
266 drying in Belize and reduced rainfall in Scotland (Fig. 4). The 1783 C.E. event was
267 previously also described in the YOK-G stalagmite record from Yok Balum Cave and
268 coincides with the peak of the strongest pre-industrial drought since 1550 C.E. in
269 Belize⁹. Additionally, we find indication of a response to volcanic forcing for the 934
270 C.E. *Eldgja* eruption in YOK-I, as well as for the 1458 C.E. *Kuwa* eruption in SU-
271 96-7. Different responses between YOK-I and SU-96-7 could be related to the season
272 of the eruption (rainfall is highest during winter in Scotland, and during summer in
273 Belize), or to differing aerosol transport paths having very different latitudinal climate
274 impacts. Moreover, chronological uncertainties in both the YOK-I and SU-96-7

275 records do not allow for a definitive attribution of these events to a volcanic trigger,
276 and remain tentative.

277 We note that most of the short-lived events recorded in Belize lag the events in
278 Scotland by ~15-20 years. This relationship is corroborated by the standard
279 correlation, which is maximized at a lag of 16 years, and by a cross correlation
280 analysis performed for the two time series (Fig. 4), which shows that nearly all the
281 visually identified events are also characterized by significant positive correlations
282 with lags of up to 40 years (with SU-96-7 leading). It is possible that such a lagged
283 response of precipitation to solar forcing is more rapidly translated to the North
284 Atlantic than to the Caribbean region (e.g., via sea ice feedbacks). However, we note
285 that the lag we find is too close to the chronological uncertainty in the two time series
286 to be robustly assigned to climatic phenomena.

287

288 Our results suggest that the low- to mid-latitude hydrologic seesaw is a feature
289 inherent to the climate system at very different timescales, with only the strength of
290 its expression varying. The presence, extent and dynamics of the hydrologic seesaw
291 over the past two millennia is remarkable given the very different boundary
292 conditions of the global climate system compared to glaciations, indicating that more
293 subtle variations in the hemispheric temperature gradient are sufficient to change the
294 meridional position of the ITCZ and the subtropical highs. This observation is only
295 possible because of the recent development of high quality records covering the last
296 two millennia. We suggest that, as chronological precision is further improved and
297 additional records become available, the hydrologic seesaw may become resolvable at
298 (multi-)annual timescales as well.

299

300 Methods:

301 Construction of the hemispheric and ITCZ stacks

302 Using the age modeling software COPRA⁴⁸, ensembles of 2,000 realizations of each
303 record's age model were computed. Subsequently, a mild tuning was performed to
304 find the best age model within the ensemble of each individual record, defined as the
305 age model that maximizes the signal correlation against all other overlapping records.
306 A 2,000 year nonlinear (Gaussian) trend was subtracted from the records prior to
307 correlation estimation to focus the alignment on centennial timescales and improve
308 the signal-to-noise ratio. Correlations between records used in the stack are estimated
309 directly from the irregular time series using Gaussian kernel correlation⁴⁹. The best
310 realizations for each proxy record are then brought to a common resolution of 10
311 years in a double-interpolation routine that minimizes aliasing of high-frequency
312 variability into the result⁵⁰. The stacks are given by the unweighted average of the
313 standardized and centralized records. An estimate of the uncertainty of this average is
314 gained from the standard error of the mean, taking into account the number of records
315 averaged at each point. This error represents a lower bound for the true uncertainty, as
316 it implicitly assumes independence amongst all datasets. The assumption of
317 independence may further give rise to a regional bias or site bias, considering that the
318 records are not distributed equally spaced around the Earth and some are closely
319 spaced. A detailed inspection of the potential impact of this location bias, for example
320 by pseudoproxy experiments using climate model output would require knowledge of
321 (or further assumptions about) the proxy signal, the signal-to-noise ratio and
322 chronological uncertainties. Hence, such a comparison is currently beyond the scope
323 of this manuscript.

324

325 Cross-correlation analysis between YOK-I and SU-96-7
326 To estimate the cross-correlation at various lags for the YOK-I $\delta^{13}\text{C}$ and SU-96-7
327 band width records, we use the framework of kernel-based cross-correlation analysis
328 by Rehfeld and Kurths (2014)⁴⁹ implemented in the toolbox NESTool
329 (<http://tocsy.pik-potsdam.de/nest.php>). We move a window of 100 years from ~900
330 C.E. to ~2000 C.E. and after extracting the portion of the record within a window, we
331 estimate the correlation with the YOK-I record being lagged up to 60 years. Statistical
332 significance of the correlation values is determined with 1000 randomised surrogates
333 of the datasets at a confidence level of $\alpha = 0.05$, corrected for multiple
334 comparisons using the Bonferroni correction factor.

335

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355

356 Author contributions:

357 S.F.M.B., G.H., J.U.L.B., K.M.P. and D.J.K. designed the study. F.A.L., K.R., B.G.,
358 and N.M. designed and performed the statistical analysis of the records. F.A.L.,
359 J.U.L.B., and S.F.M.B. wrote the manuscript and contributed to figure drafting. Y.A.,
360 V.V.A., and V.P. developed the original YOK-I ²³⁰Th chronology and assisted with
361 data interpretation. F.A.L., H.E.R. and S.F.M.B. built the YOK-I age model. K.M.P.
362 holds the Yok Balum Cave fieldwork permit, and assisted F.A.L., J.U.L.B., H.E.R.,
363 and S.F.M.B. during fieldwork. D.J.K. lab group sampled the YOK-I speleothem and
364 S.F.M.B. performed the isotope analysis. H.E.R. assisted with data interpretation.
365 G.H. and T.I.E. assisted and edited the manuscript. All named co-authors contributed
366 to the project, discussed manuscript ideas, and approved the final manuscript.

367

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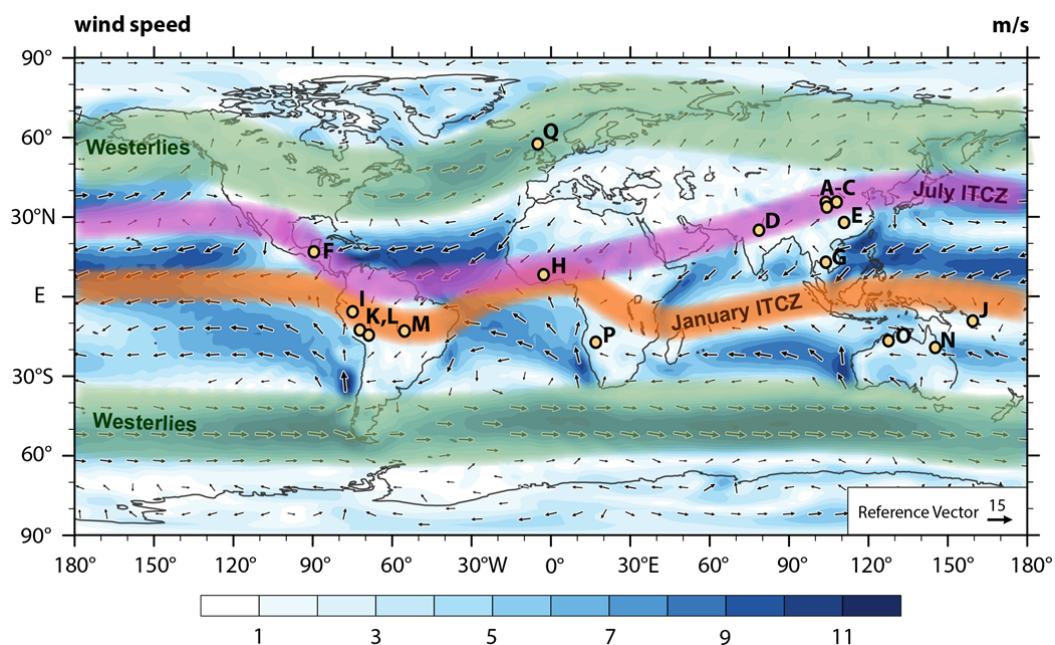
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538

539

540 Figures:



541

542 Fig.1: Map depicting the locations of the records presented in this study: A –
 543 Stalagmites HY1 and HY2 from Huangye cave, China⁵¹; B – Stalagmite WX42B
 544 from Wanxiang cave, China⁵²; C – Stalagmite DY1 from Dayu Cave, China⁵³; D –
 545 Stalagmites SAH-A and SAH-B from Sahiya Cave, India⁵⁴; E – Stalagmite A1 from
 546 Lianhua Cave, China⁵⁵; F – Stalagmite YOK-I from Yok Balum cave, Belize⁸; G –
 547 Tree ring reconstruction from Bidoup Nui Ba National Park, Vietnam⁵⁶; H – Sediment
 548 record from Bosumtwi Lake, Ghana⁵⁷; I – Stalagmite CAS-D from Cascayunga cave,
 549 Peru⁵⁸; J – Stalagmites 10FC-02 and 05FC-04 from Forestry Cave, Guadalcanal,
 550 Solomon Islands²³; K – Stalagmites P00-H1 and P09-H2 from Huagapo cave, Peru⁵⁹;
 551 L – Ice core from the Quelccaya ice cap, Peru⁶⁰; M – Stalagmites from Curupira and
 552 Pau d’Alho Caves, Brazil⁶¹; N – Stalagmite CH-1 from Chillagoe, Australia⁶²; O –
 553 Stalagmites KNI-51 F, G, I, O, P, and 11 from KNI-51 Cave, Australia⁶³; P –
 554 Stalagmite DP1 from Dante cave, Namibia^{21,22}; Q – Stalagmite SU-96-7 from Uamh-
 555 an-Tartair cave, Scotland¹¹. Winter wind vectors in the background are derived from
 556 1950-2000 reanalysis data provided by the 20th Century Reanalysis Composites from
 557 the NOAA Earth System Research Laboratory, Physical Science Division. The map
 558 was created using the NCAR Command Language (Version 6.3.0), 2016, Boulder,
 559 Colorado: UCAR/NCAR/CISL/TDD. <http://dx.doi.org/10.5065/D6WD3XH5>.

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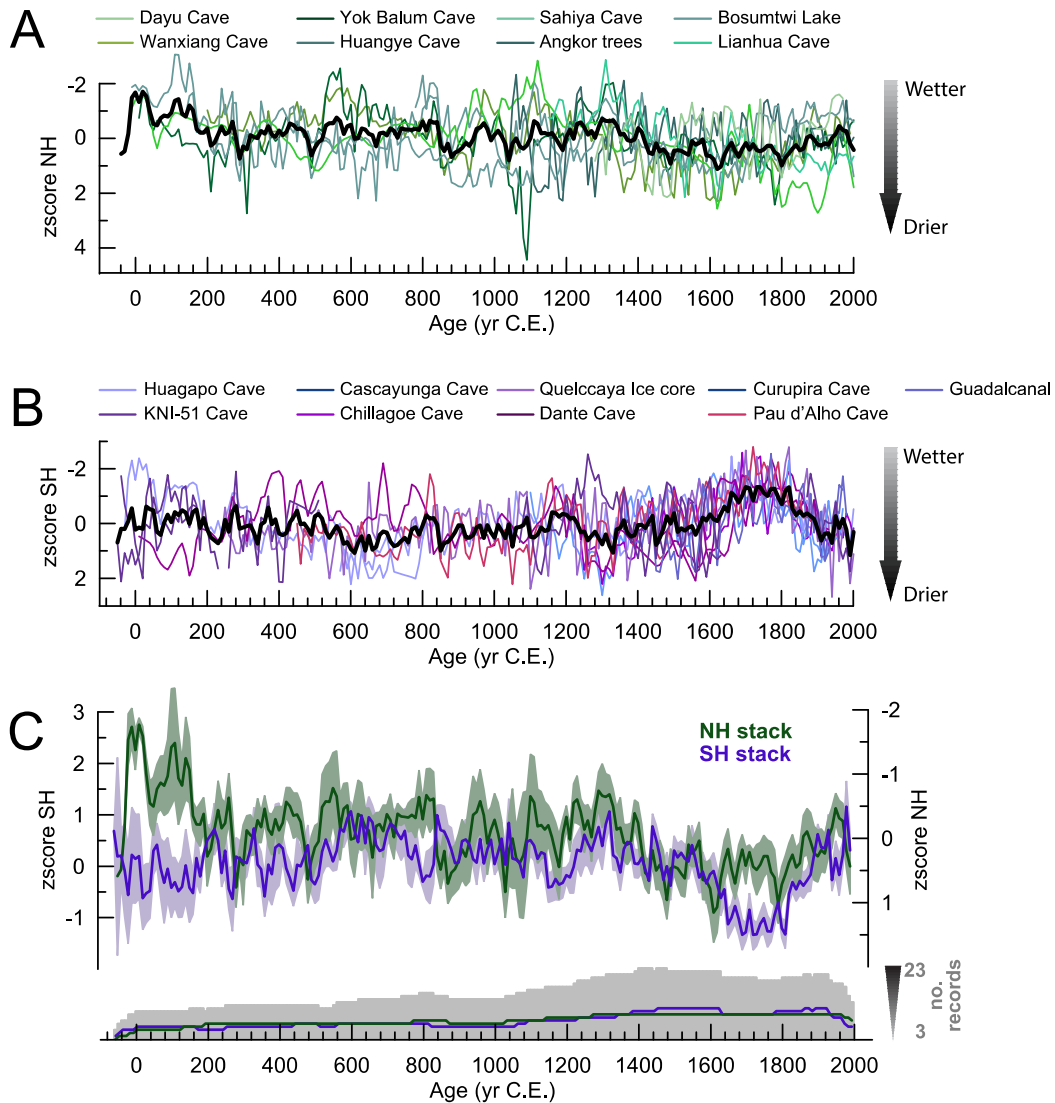
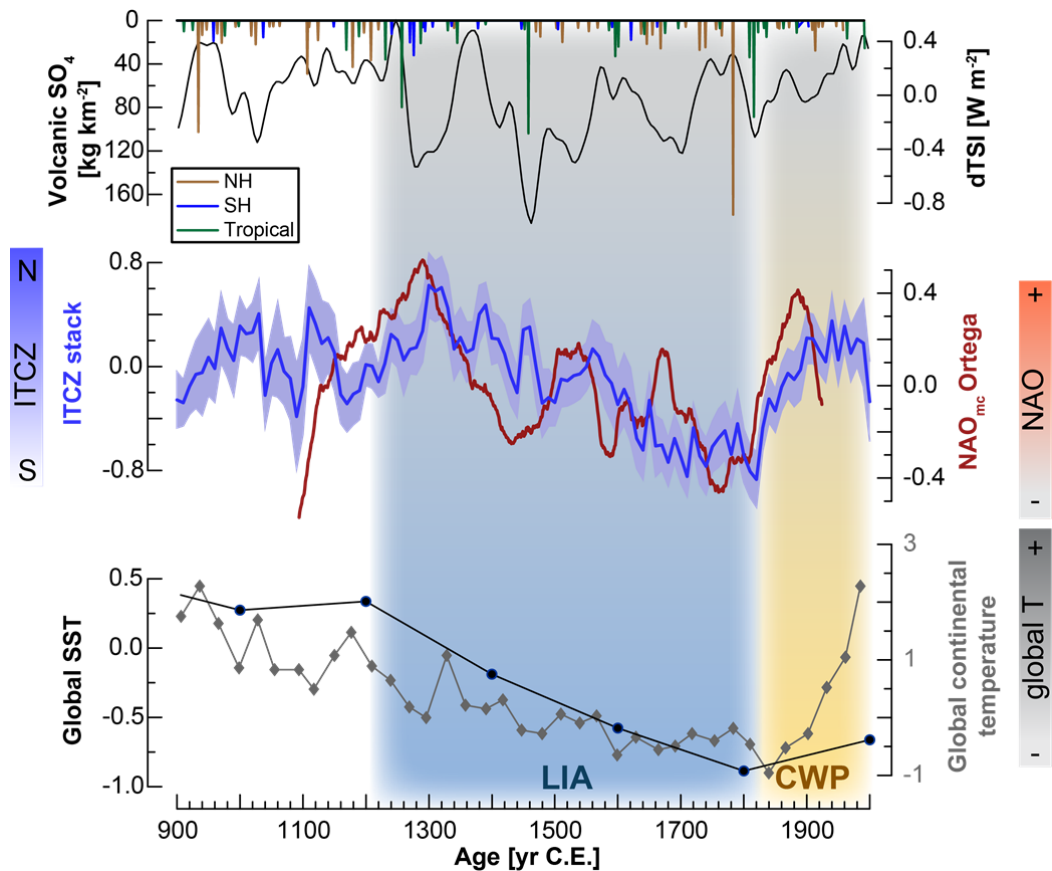
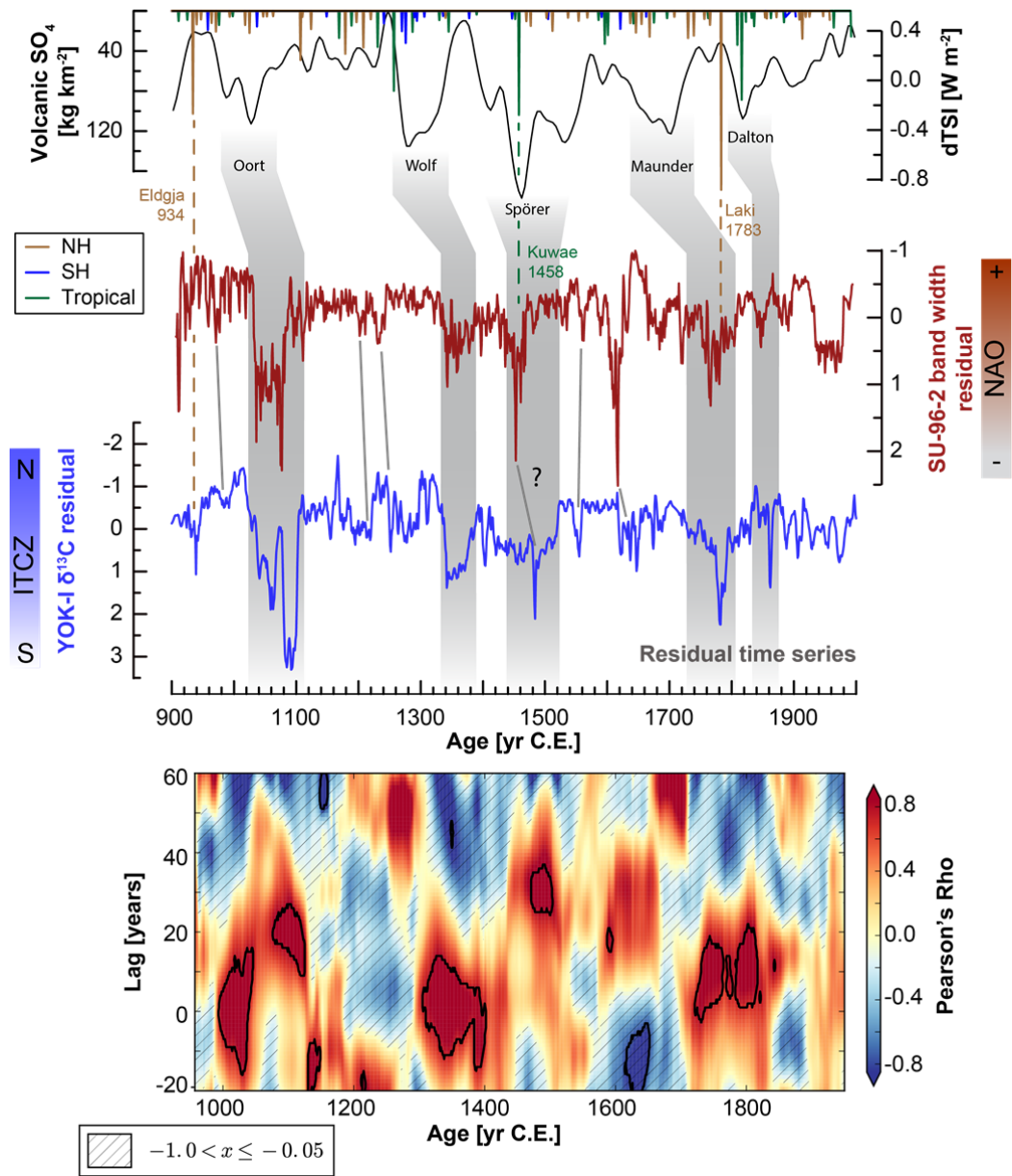


Fig. 2: NH and SH ITCZ record stacks. All records have been converted to z-scores. A – NH record compilation, the resulting stack is shown by the black line. B – SH record compilation, the resulting stack is shown by the black line. C – Both NH and SH stacks are shown with their uncertainties: antiphasing of the two stacks on centennial timescale becomes apparent, especially during the period 1320-1820 C.E.



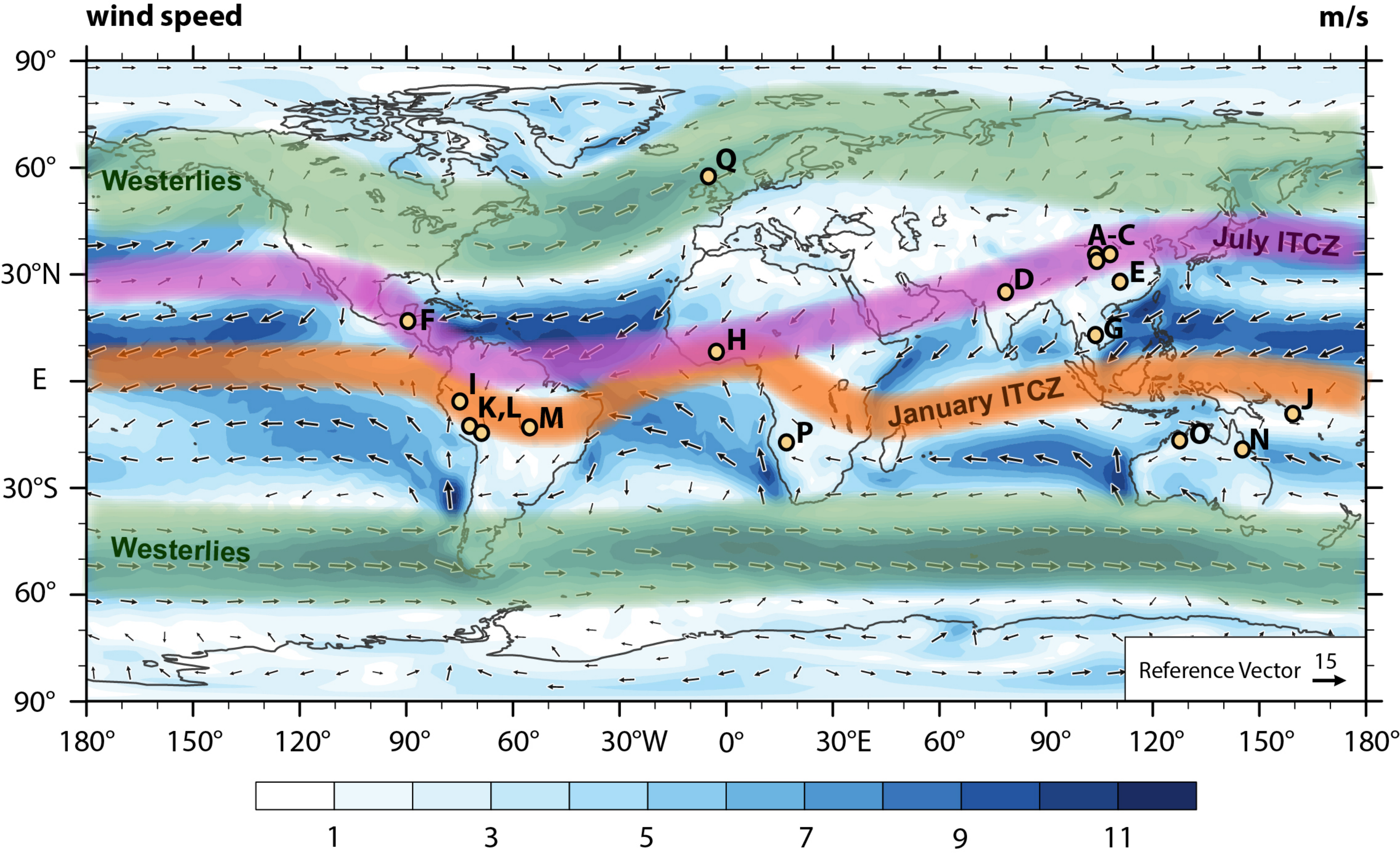
568
 569 Fig. 3: Comparison of records to the ITCZ-stack over the last ~1000 years. From top:
 570 Volcanic sulfate (SO_4) recorded in ice cores from Antarctica and Greenland⁴⁰, and
 571 solar forcing (dTSI) from ^{10}Be in ice cores⁶⁴. Note that solar and volcanic activity are
 572 plotted independently from their radiative forcing, which is much stronger for
 573 volcanic eruptions than for solar activity. Model-constrained multi-proxy NAO
 574 reconstruction by Ortega et al. 2015⁶ with 91-point running average to highlight
 575 decadal-centennial trends. ITCZ-stack (this study), showing relative meridional ITCZ
 576 deflection over time. Global continental temperature reconstruction by the PAGES 2k
 577 consortium¹⁹ (grey line), and global sea surface temperature (SST) reconstruction by
 578 McGregor et al.²⁰ (black line). The intervals of the Little Ice Age (LIA, 1450-1850
 579 C.E.) and Current Warm Period (CWP, after 1850), defined as in the IPCC AR5⁶⁵, are
 580 highlighted with background shading.

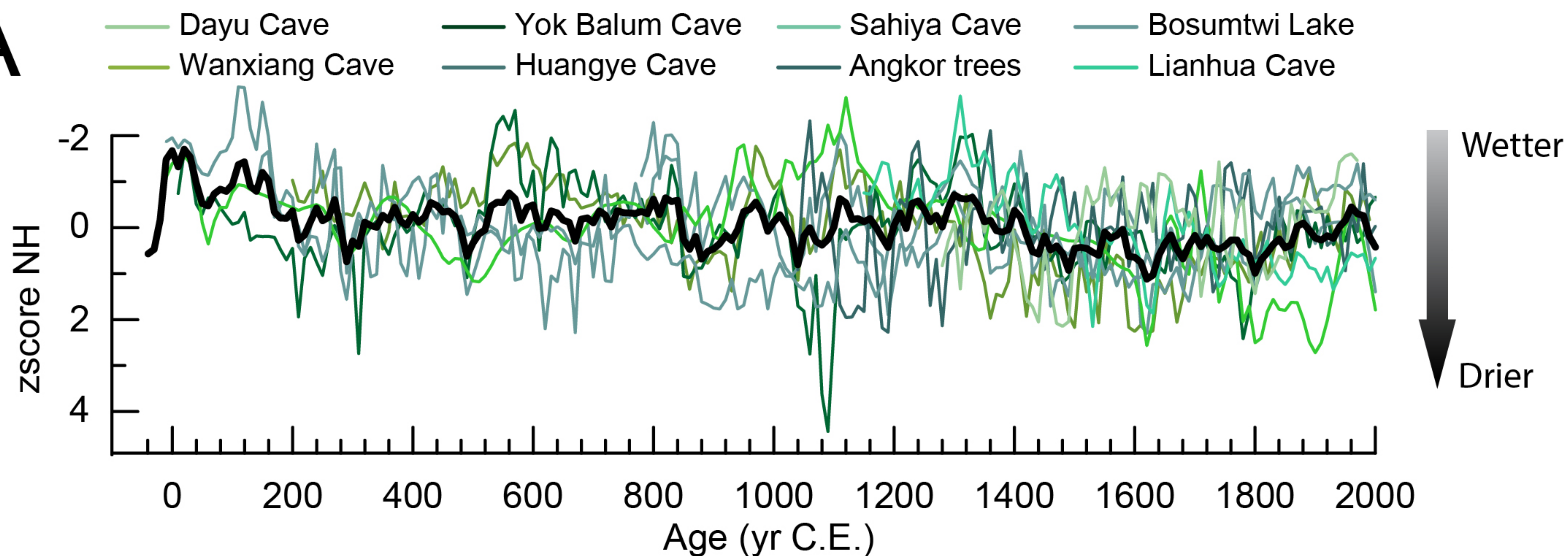
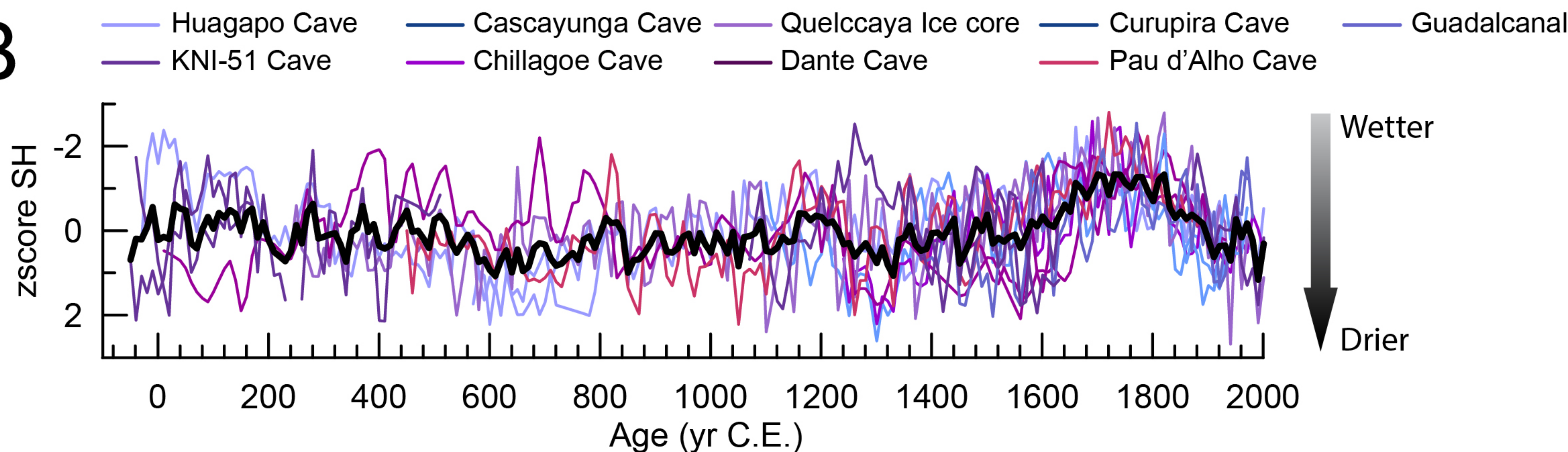


582

583 Fig. 4: Comparison of short-term variations in hydroclimate between low- and mid-
584 latitudes in the NH. The residuals of the smoothed YOK-I and SU-96-7 records are
585 shown in the middle of the figure. Events thought to have occurred in both records
586 highlighted by grey lines. Volcanic sulfate recorded in ice cores from Antarctica and
587 Greenland ⁴⁰, as well as solar forcing from ¹⁰Be in ice cores ⁶⁴, are shown at the top of
588 the figure. Volcanic eruptions tentatively identified in the proxy records are indicated

589 by dashed lines and the eruption name and year. Solar minima recorded with a lag in
590 the proxy records are shown by the grey bars. The color coded plot at the bottom of
591 the figure shows the lagged cross correlation between the YOK-I $\delta^{13}\text{C}$ and SU-96-7
592 band width records for their common time duration (~900-2000 C.E.). The time
593 evolution of the lagged correlation was obtained using a sliding window of 100 years
594 and allowing for a maximum lead of 60 years to the SU-96-7 record. We find
595 statistically significant correlations between lags of 0-10 years at around 1000, 1300-
596 1400, and 1700-1810 C.E., and lags of 10-20 years during the 1020-1100 C.E. event.
597 Hatched regions in the plot indicate negative correlation values and statistically
598 significant regions of correlation are marked with a thick black boundary.



A**B****C**